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Responses of planted conifers and natural hardwood regeneration to harvesting, scalping, and weeding on a boreal mixedwood site

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Abstract

Recent emphasis on ecosystem-based forest management has increased interest in promoting species mixtures to enhance stand-level diversity. However, there is little information on silvicultural approaches to regenerate mixtures of conifers and hardwoods in northern Ontario. This study tested fifth-year effects of harvest intensity (uncut, 50% partial cut with and without removal of residuals after 3 years, and clearcut), site preparation level (none and scalped), and chemical weeding frequency (none, single, and multiple) on survival and growth of planted white spruce (*Picea glauca* [Moench] Voss) and jack pine (*Pinus banksiana* Lamb.), height and density of hardwood regeneration, and cover of competing shrubs. The study is located in a hardwood-dominated mixedwood stand on a fertile, mesic, upland site in northeastern Ontario. Although throughfall precipitation, wind speed, and temperature were moderated by residual cover, only light level varied sufficiently among treatments to account for differences in regeneration success. Damage to regeneration by mammals, weather, or equipment was minor, but up to 17% of residual basal area was lost to windthrow in partial cuts. Scalping had no effect on the development of conifer seedlings, hardwood regeneration, or shrubs. Survival of conifer seedlings was enhanced by harvesting but not by weeding, and spruce survival exceeded pine survival at all harvest levels. Seedling height and diameter growth increased with harvest intensity and weeding frequency, and the beneficial effects of weeding increased with harvest intensity. Height and density of hardwood regeneration increased with harvest intensity and decreased with weeding frequency. Single weeding reduced but did not eliminate hardwoods. Harvesting slightly increased shrub cover and weeding sharply decreased it. Dense suckering of trembling aspen (*Populus tremuloides* Michx.) followed removal of residuals 3 years after the initial 50% partial cut. Thus, final removal cuts on mixedwood sites should be delayed until conifer seedlings are well established. Underplanting cannot be recommended for uncut mixedwood stands in Ontario because of unacceptably high seedling mortality. Compared to clearcutting, partial cutting without removal of residuals reduced fifth-year hardwood density on unweeded plots. However, hardwoods on that treatment overtopped spruce seedlings by 90 cm and pine seedlings by 64 cm. Partial cutting with reduced weeding produced acceptable stocking of conifer and hardwood regeneration, but did not promote seedling growth. Weeding was required to maintain spruce as a viable understory component, to ensure pine codominance with hardwoods, and to reduce shrub cover below 50%. Separating species into alternating patches or corridors may be more productive than promoting integrated mixtures, since it allows silvicultural treatments to be adapted to the needs of each species. Long-term monitoring of crop trees and associated vegetation following mixedwood management options on a range of boreal sites is required to advance the knowledge base and produce reliable operational guidelines.
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Keywords: Boreal mixedwood management; Herbicide; Partial cutting; *Picea*; *Pinus*; *Populus*; Seedling response; Underplanting

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1. Introduction

Ontario's boreal mixedwood forests are ecologically and economically valuable, occupying half of the productive forest land within the southern Boreal Forest Region and northern Great Lakes-St. Lawrence Forest Region (McClain, 1981). This amounts to approximately 160,000 km^2 of mixedwood forest.

The species composition of young boreal forests in Ontario is shifting towards mixedwoods and hardwoods (Hearnden et al., 1992), despite attempts to establish pure conifer stands after harvesting. This expansion of mixedwoods emphasizes the importance of developing silvicultural guidelines for these forest types. Mixed forests offer many advantages over single-species stands, such as a wider range of wood products, less expensive regeneration, improved aesthetics, more diverse wildlife habitat, increased pest resistance, and enhanced nutrient cycling (Lieffers and Beck, 1994; MacDonald, 1995; Bergeron et al., 1998).

Ecosystem management often emphasizes landscape-scale interventions (Swanson and Franklin, 1992; Angelstam and Petterson, 1996; Yaffee, 1999; Harvey et al., 2002). However, a key aspect of ecosystem management is maintenance of compositional and structural diversity at all scales, which protects important ecological processes (Simard, 1996; Landers et al., 1999) and ensures adaptability to changing conditions (Maser, 1994). Mixedwood management supports this approach by promoting biological diversity and adapting to successional changes (Weingartner and MacDonald, 1995).

Interest in deliberate management of species mixtures has recently developed in many parts of the world (e.g., Brace Forest Services, 1992; Bradshaw and Gemmel, 1992; Norokorpi, 1992; Irland and Maass, 1994; Lieffers and Beck, 1994; Parviainen, 1994; Bergeron and Harvey, 1997). Alternative practices to promote mixtures of trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* [Moench] Voss) are being developed in western Canada (Navratil, 1996; Ball and Walker, 1997), and researchers in Quebec are seeking mixedwood silvicultural techniques modelled after natural disturbance patterns (Bergeron and Harvey, 1997). Resource managers in Ontario have recently begun to promote boreal mixedwood management and acquire applied knowledge on regenerating desired species mixtures.

The objective of this study is to reduce uncertainty about the silvicultural approaches required to obtain mixtures of conifer and hardwood regeneration on hardwood-dominated boreal mixedwood sites in Ontario. The emphasis is on techniques for securing adequate stocking and growth of conifer regeneration, one of the most challenging aspects of boreal mixedwood management (Brace Forest Services, 1992). Since chemical weeding may damage hardwood crop trees and raise public concern about health risks, partial cutting (to maintain shade) combined with reduced weeding may be a desirable option for enhancing conifer regeneration in mixedwood stands. This approach should limit competition from aspen suckers because their initiation and development are inhibited by low soil temperatures and light levels (Burns and Honkala, 1990). Conifer seedlings should benefit from weeding to reduce competition (enhancing light and nutrient availability) and scalping to remove localized vegetation and expose mineral soil for the rooting medium at the time of planting (enhancing moisture availability). Thus, it was hypothesized that optimum stocking and growth of mixed conifer and hardwood regeneration could be achieved by combining partial cutting with scalping, underplanting, and limited chemical weeding.

2. Methods

The study was established in an upland mid-successional boreal mixedwood stand north of Chapleau, Ontario, at 47° 59′N latitude, 83° 25′W longitude. The overstory was dominated by 70-year-old trembling aspen and white birch (*Betula papyrifera* Marsh.), with a 20% component of codominant conifers, including black spruce (*Picea mariana* [Mill] B.S.P.), white spruce, jack pine (*Pinus banksiana* Lamb.), and balsam fir (*Abies balsamea* [L.] Mill.). Understory vegetation was predominantly balsam fir, white spruce, and hardwood shrubs such as mountain maple (*Acer spicatum* Lamb.) and beaked hazel (*Corylus cornuta* Marsh.), on fresh to moist, non-calcareous, coarse loamy soils.

Four intensities of overstory basal area removal were randomly applied to 112 m × 56 m main plots: (1) uncut; (2) 50% partial cut without removal of residuals (PC50); (3) 50% partial cut with residuals

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removed after 3 years (PC100); (4) clearcut. Three weeding frequencies (none, single, multiple) and two site preparation levels (none, scalped) were randomly applied to 14 m × 14 m sub-plots within each main plot. A 14 m harvested buffer separated each group of sub-plots from adjacent harvest treatments, and a 2 m buffer separated adjacent sub-plots. A split-plot experimental design was used, with a randomized complete block arrangement of main treatments (harvest intensities) and a factorial arrangement of secondary treatments (weeding frequencies and site preparation levels). There were six replications of all treatment combinations.

The main plots were full-tree logged with a feller-buncher in the winter of 1993–1994, preferentially removing dominant aspen and fir. Spruce was cut only if necessary to achieve the required basal area reductions. Regular, oblique entries into each plot from 5 m wide skid trails on both sides created a herringbone pattern similar to that reported by Froning (1980) for harvesting hardwoods while protecting understory conifers. Careful logging conducted with snow cover and frozen ground minimized damage to the site and residual trees.

Clearcutting removed overstory trees greater than 10 cm diameter at breast height (DBH), leaving saplings and advance growth that will form part of the next crop. Some trees exceeding 10 cm DBH remained on clearcut plots after treatment because they were either unmerchantable or could not be removed without excessive damage to advance growth.

Each sub-plot was planted with 42 overwintered container seedlings from local seed sources in the spring of 1994, in a 6 × 7 grid at 2 m spacing. Since there are no formal mixedwood stocking standards in Ontario, conifers were planted at a generally accepted operational spacing for pure stands. A wider spacing may be feasible for species mixtures, but it would provide less insurance against mortality of conifer seedlings. Consistently high stock quality was ensured by the Ontario Stock Quality Assessment Program (Sampson et al., 1997), which performed visual assessments and measured chlorophyll fluorescence and root growth potential on 150 randomly selected seedlings per stock lot. Half the sub-plots were planted with white spruce, and half with jack pine. Analyses were repeated for each species, rather than incorporating species as another factor in the design.

For each species, half the planting spots were manually scalped before planting by removing the humus layer within a 25 cm radius. Multiple-weeded sub-plots were ground-sprayed with glyphosate (1.7 kg ha^{-1} acid equivalent) following seedling bud set for 5 years after harvesting, while single-weeded plots were sprayed only in the second year.

The ground cover of shrubs and densities and heights of hardwood tree regeneration were recorded annually prior to weeding on four vegetation assessment plots (2 m × 2 m) within each sub-plot. Survival, height, and leader-base diameter were measured on all planted seedlings following bud set. Leader diameter effectively quantifies current growth because it includes only the most recent growth ring. The number of seedlings in each sub-plot damaged by mammals or abiotic agents was also recorded.

One replication of each harvesting treatment was instrumented to monitor surface soil temperature, air temperature at 2 m above ground, precipitation at 0.5 m, wind speed at 3.6 m, and photosynthetically active radiation (PAR) at 1 m. All variables were recorded every 30 s and averaged every 20 min, using a CR21X data logger (Campbell Scientific, Edmonton, Alta.). Measurements continued from early June until late September during the first 5 years after harvesting. Since the sensors were located in unweeded sub-plots, differences in microclimatic variables among main plots reflected only the effect of harvest intensity. Growing season means were based on 24 h days for all variables except PAR, which was based on 12 h days (07:00–19:00 h EDST).

Analysis of variance (ANOVA) was used to assess fifth-year effects of treatments and interactions on the responses of planted seedlings (survival, height, leader diameter), natural hardwood regeneration (height, density), and competing shrubs (ground cover percent). A priori contrasts to test response differences among treatment levels included comparison of uncut to partial cuts, clearcut to partial cuts, and PC50–PC100 within the harvest intensity treatment, and comparison of unweeded to weeded and single-weeded to multiple-weeded within the weeding frequency treatment.

An assessment of the normal probability quantile–quantile (qq) plot and residual scatter plot determined whether a transformation was necessary to satisfy the assumptions of ANOVA for each response variable.

If the assumption of normality or homogeneity of variance was violated, a Box–Cox power transformation (Montgomery, 1976; Steele et al., 1997) was calculated for an appropriate range of exponents, and the exponent that minimized the error mean square was selected. The ANOVA was repeated using a common function near the selected power transformation (e.g., if an exponent of 0.4 minimized the error mean square, then a square root transformation would be applied). Transformations were used for seedling height (natural logarithm) and leader diameter (square root), but were not required for the other response variables. Analyses were conducted with S-plus statistical software (MathSoft, 1999).

Interaction graphs were constructed to help interpret responses of crop trees and shrubs to treatments. These graphs are meant to reveal the nature and degree of interactions among factors, not to illustrate functional relationships. Thus, quantitative levels or qualitative classes (as in this study) may be used as abscissa-axis intervals (Hicks, 1982). While response lines in an ordinal interaction do not cross and the main effect of the factor represented by the lines may be interpreted, lines in a disordinal interaction cross and the effect of the factor represented by the lines may only be interpreted for each level of the other factor (Keppel, 1991).

3. Results

Fifth-year assessments of the regeneration environment and damage to regeneration are presented as descriptive information. The effects of harvesting and weeding are emphasized in presenting fifth-year responses of crop tree regeneration and shrubs, since scalping produced no significant responses.

3.1. Regeneration environment

The basal area of uncut overstory increased gradually during the first 5 years of the study (Table 1). However, between the first and third years mean residual basal area ($m^2\ ha^{-1}$) decreased from 18.9 to 15.6 in the PC50 treatment, from 18.4 to 16.8 in the PC100 treatment, and from 1.5 to 1.0 in the clearcut treatment. These results reflect a greater windthrow risk to both conifers and hardwoods after opening the stands, as indicated by field observations. Windthrow loss was most pronounced immediately after harvesting, and by the fifth year basal area increment exceeded windthrow loss in the clearcut and PC50 treatments. This net increase did not occur in the PC100 treatment because it was harvested again in 1997.

Based on data from the instrumented replication during the fifth post-treatment growing season, minimum air temperature decreased with harvest intensity, while all other measured microclimatic variables increased (Table 2). The relative change associated with harvesting was greatest for PAR, followed by wind speed, precipitation, minimum air temperature, mean soil temperature, and mean air temperature. Compared to the clearcut treatment, the PC50 treatment averaged 38% PAR and the uncut control only 6% PAR (Table 2).

Table 1
Changes in overstory basal area for all harvest intensities during the first 5 years after harvesting

Harvest intensity	1994[a] basal area			1996 basal area			1998 basal area		
	Mean ($m^2\ ha^{-1}$)	S.D.[b]	Residual[c] (%)	Mean ($m^2\ ha^{-1}$)	S.D.	Residual (%)	Mean ($m^2\ ha^{-1}$)	S.D.	Residual (%)
Uncut	36.9	1.99	101.5	37.7	2.49	103.5	38.4	2.53	105.5
PC50[d]	18.9	4.16	51.1	15.6	2.71	42.2	16.1	2.80	43.5
PC100[e]	18.4	3.62	55.7	16.8	4.15	51.0	1.1	0.27	3.3
Clearcut	1.5	0.80	4.1	1.0	0.68	2.9	1.7	1.17	4.7

[a] First post-harvest measurement in summer 1994, following harvesting in previous winter.
[b] Standard deviation.
[c] Expressed as a percentage of pre-harvest level, based on trees ≥10 cm DBH.
[d] Partial cut removing 50% of the basal area in a single entry.
[e] Partial cut removing 50% of the basal area in the first entry, followed by residual removal 3 years later.

Table 2
Microclimatic factors compared among harvest levels during the fifth growing season after harvesting

Harvest intensity	Mean PAR[a] (mmol m^{-2})	Mean air temperature[b] (°C)	Minimum air temperature[b] (°C)	Mean soil temperature[c] (°C)	Total precipitation[d] (mm)	Mean wind speed[e] (km h^{-1})
Uncut	50.0	17.0	−3.3	13.0	238.2	0.8
PC50[f]	314.6	17.6	−3.3	14.0	265.1	1.1
PC100[g]	853.8	18.3	−3.7	13.8	364.3	2.2
Clearcut	822.6	18.5	−3.9	14.7	318.4	1.2

[a] Total flux of PAR 1 m above ground.
[b] Sensors 2.0 m above ground.
[c] Sensors 2.5 cm below ground.
[d] Sensors 50 cm above ground.
[e] Sensors 3.6 m above ground.
[f] Partial cut removing 50% of the basal area in a single entry.
[g] Partial cut removing 50% of the basal area in the first entry, followed by residual removal 3 years later.

3.2. Damage to regeneration

Girdling and browsing of crop tree regeneration were infrequently observed. Jack pine had the most damage, followed by hardwoods and white spruce, but in no case did damage exceed 4% of the sample trees 5 years after treatment (Table 3). There was insufficient range in the data to reveal differences in mammal damage among the harvesting, weeding, or scalping treatments. However, abiotic damage to regeneration was greater in harvested treatments than in uncut controls. Damage decreased with increased harvest intensity in harvested treatments.

3.3. Seedling survival

Although main weeding effects and interactions between harvesting and weeding were not significant,

Table 3
Damage to planted seedlings and natural hardwood regeneration compared among treatments during fifth growing season after harvesting

Treatment	Damage by mammals[a] (percentage of trees)						Abiotic damage[b] (percentage of trees)					
	White spruce		Jack pine		Hardwoods		White spruce		Jack pine		Hardwoods	
	Mean	S.D.[c]	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Harvesting												
Uncut	0.07	0.16	2.85	1.81	1.34	1.52	2.74	2.15	1.46	0.84	3.99	4.02
PC50[d]	0.00	0.00	3.41	1.02	1.75	1.23	6.81	1.37	7.96	2.91	6.63	2.57
PC100[e]	0.07	0.16	3.68	1.93	1.08	0.60	6.19	2.33	6.25	2.33	5.50	1.99
Clearcut	0.07	0.16	1.10	1.06	3.75	3.44	5.63	3.02	5.86	2.92	5.47	4.09
Weeding												
None	0.10	0.17	2.89	1.47	3.06	2.73	6.02	2.78	6.71	3.64	6.46	3.00
Single	0.00	0.00	3.12	1.94	1.74	2.02	5.50	2.87	4.65	2.55	7.21	2.99
Multiple	0.05	0.13	2.26	1.87	1.14	1.37	4.50	2.43	4.79	3.50	2.51	2.13
Scalping												
Not scalped	0.03	0.10	2.35	1.54	2.06	1.78	5.29	3.07	4.52	2.64	5.88	2.94
Scalped	0.07	0.16	3.17	1.18	1.90	2.66	5.39	2.44	6.25	3.82	4.91	3.79

[a] Stem girdling, branch clipping, or foliage browsing.
[b] Breakage, wounding, or uprooting.
[c] Standard deviation.
[d] Partial cut removing 50% of the basal area in a single entry.
[e] Partial cut removing 50% of the basal area in the first entry, followed by residual removal 3 years later.

Table 4
Summary of *P*-values (probabilities of a greater *F*-value occurring by chance) from ANOVA for fifth-year response variables of planted seedlings and other understory vegetation

Source of variation[a]	d.f.[b]	Planted seedlings						Other vegetation		
		Survival		Height[c]		Leader diameter[d]		Hdwd height[e]	Hdwd density[f]	Shrub cover[g]
		Spruce	Pine	Spruce	Pine	Spruce	Pine			
Harvesting (H)	3	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.041
Uncut:partial cuts	(1)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.095
Clearcut:partial cuts	(1)	0.001	0.004	<0.001	<0.001	<0.001	<0.001	<0.001	0.030	0.042
PC50[h]:PC100[i]	(1)	0.297	0.038	0.923	0.452	<0.001	0.013	0.203	<0.001	0.141
Weeding (W)	2	0.079	0.128	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Unweeded:weeded	(1)	0.313	0.766	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Single:multiple	(1)	0.044	0.045	0.001	0.153	<0.001	0.001	<0.001	<0.001	<0.001
Scalping (S)	1	0.540	0.062	0.147	0.277	0.670	0.062	0.613	0.324	0.086
H × W	6	0.348	0.829	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	0.306
H × S	3	0.083	0.155	0.586	0.834	0.965	0.666	0.611	0.676	0.835
W × S	2	0.276	0.556	0.892	0.485	0.777	0.958	0.903	0.177	0.308
H × W × S	6	0.423	0.992	0.829	0.529	0.971	0.564	0.674	0.283	0.983

[a] Planned orthogonal contrasts are shown under the two main effects that have more than one degree of freedom.
[b] Degrees of freedom.
[c] Natural logarithm transformation applied prior to analysis.
[d] Square root transformation applied prior to analysis.
[e] Mean height of regenerating hardwood tree species, primarily trembling aspen and white birch.
[f] Mean density of regenerating hardwood tree species.
[g] Ground cover of woody perennial shrubs.
[h] Partial cut removing 50% of the basal area in a single entry.
[i] Partial cut removing 50% of the basal area in the first entry, followed by residual removal 3 years later.

harvest level significantly affected survival of white spruce and jack pine (Table 4 and Fig. 1). Mean survival of white spruce was significantly lower in the uncut control (46%) than in the partially cut treatments (85%) (Table 4 and Fig. 1a), but did not differ significantly between PC50 (88%) and PC100 (82%). Overall survival was significantly higher in the clearcut (90%) than the partially cut treatments (85%), although survival in the PC50 treatment (91%) exceeded that in the clearcut (87%) when a single weeding was applied (Fig. 1a).

Mean survival was lower for jack pine than for white spruce in all treatments (Fig. 1). As with white spruce, jack pine survival was significantly lower in the uncut control (28%) than in the partially cut treatments (73%) (Table 4 and Fig. 1c). Unlike white spruce, mean survival of jack pine differed significantly between partial cutting treatments (81% for PC50, 65% for PC100). Jack pine survival was highest in the PC50 treatment except in single-weeded plots, where survival was highest in the clearcut (83%).

3.4. Seedling height

The interaction between harvesting and weeding was significant for fifth-year white spruce height response (Table 4). In general, the effect of weeding increased with harvest intensity, although the difference in height response between the PC50 and PC100 treatments was not significant. The two partial cuts had similar height responses across the range of weeding frequency (Fig. 2a), and grouping them into a single treatment produces an ordinal interaction. Since the lines representing the uncut, grouped partially cut, and clearcut treatments do not cross (Fig. 2a), main effect contrasts for harvest intensity (Table 4) may be interpreted. White spruce height in the clearcut treatment (71 cm) was significantly greater than height in partially cut treatments (46 cm), which in turn was significantly greater than height in the uncut control (24 cm) (Fig. 2a).

Plotting white spruce height over harvest intensity for the three weeding frequencies also produces an

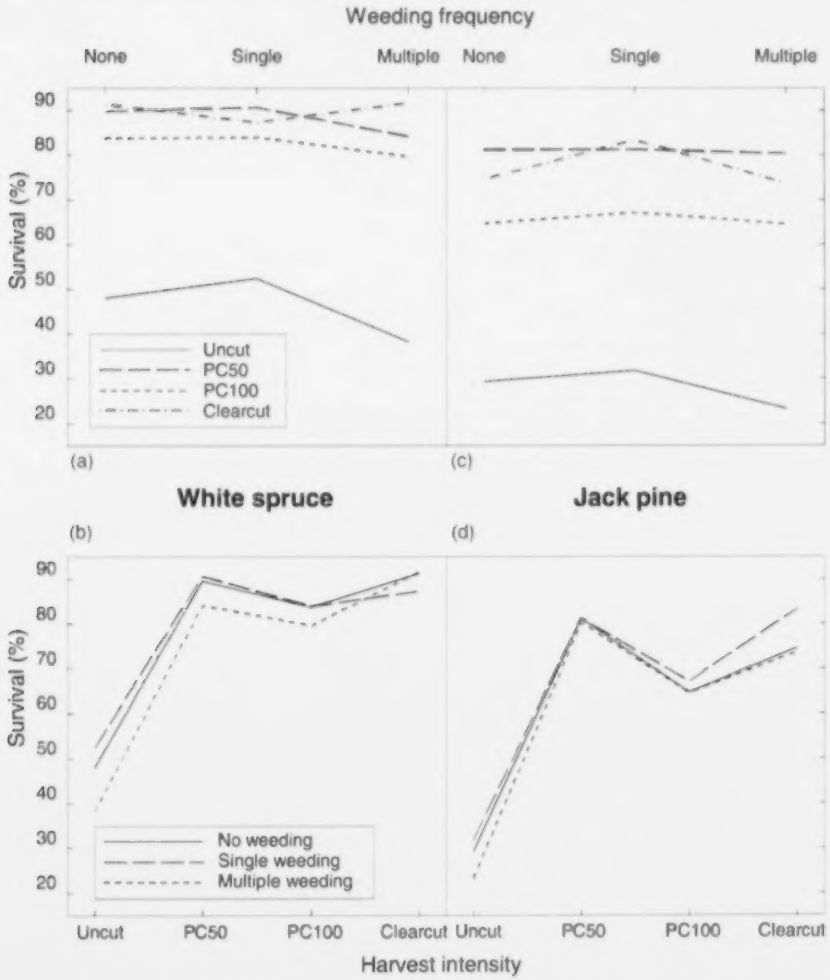

Fig. 1. Mean survival of white spruce and jack pine seedlings in response to weeding frequency and harvest intensity.

ordinal interaction (Fig. 2b). Seedling height in weeded plots (50 cm) was significantly greater than that in unweeded plots (40 cm), and height in multiple-weeded plots (54 cm) was significantly greater than that in single-weeded plots (47 cm).

The interaction between harvest intensity and weeding frequency was significant for jack pine height (Table 4). As with white spruce, the weeding effect generally increased with harvest intensity (Fig. 2c). The difference in jack pine height response between the partial cutting treatments was not significant, and mean height declined from the clearcut treatment (130 cm) to the partial cutting treatments (78 cm) to the uncut control (33 cm) (Fig. 2c). Jack pine mean height was significantly greater in weeded plots (87 cm) than in unweeded plots (69 cm), and multiple weeding was associated with a height advantage only in the clearcut treatment (Fig. 2d).

3.5. Seedling leader diameter

The interaction between harvest intensity and weeding frequency was significant for the fifth-year leader diameter responses of both conifer species (Table 4).

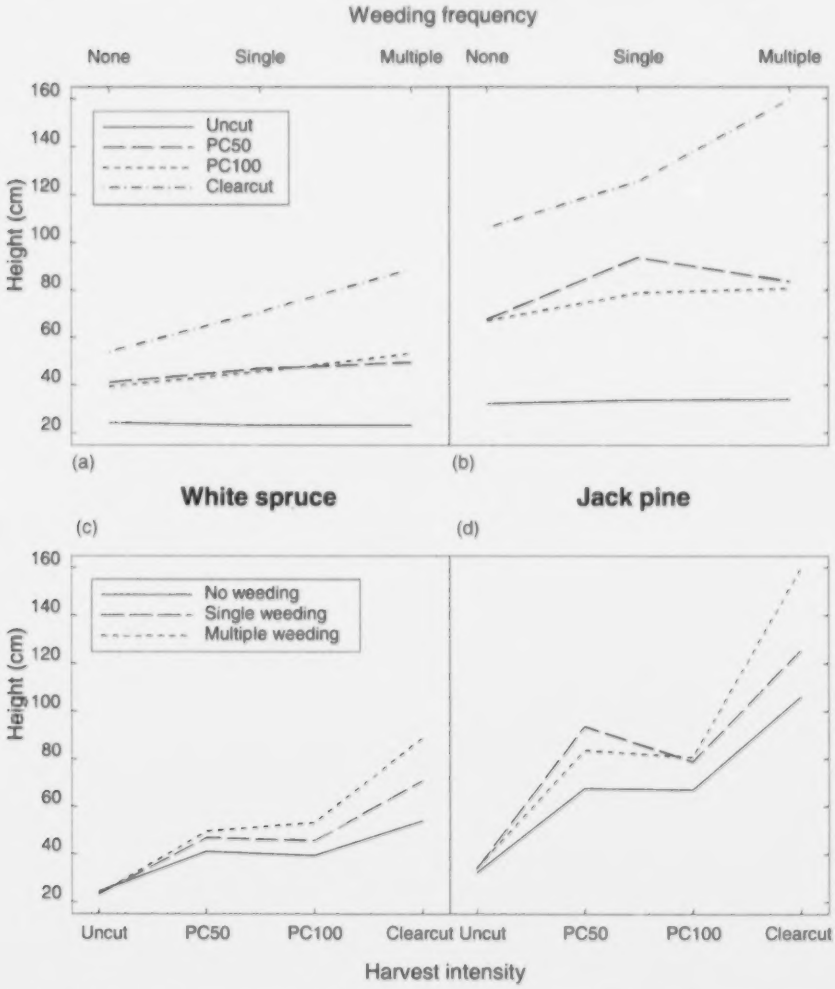

Fig. 2. Mean height of white spruce and jack pine seedlings in response to weeding frequency and harvest intensity.

The diameter response to weeding frequency increased with harvest intensity (Fig. 3a and c).

Considering contrasts for harvest intensity, mean leader diameter of white spruce in the clearcut treatment (4.5 mm) was significantly greater than mean diameter in partially cut treatments (3.1 mm), which in turn was significantly greater than mean diameter in the control (1.1 mm) (Table 4 and Fig. 3a). Also, mean diameter in the PC100 treatment (3.7 mm) was significantly greater than that in the PC50 treatment (2.6 mm). Considering contrasts for weeding frequency, mean diameter in weeded plots (3.4 mm) was significantly greater than that in unweeded plots (2.0 mm), and mean diameter in multiple-weeded plots (3.8 mm) was significantly greater than that in single-weeded plots (3.1 mm) (Table 4 and Fig. 3b).

Jack pine mean diameter in the clearcut treatment (9.0 mm) was significantly greater than that in the partially cut treatments (5.4 mm), which in turn was significantly greater than that in the control (1.3 mm) (Table 4 and Fig. 3c). Also, mean diameter in the

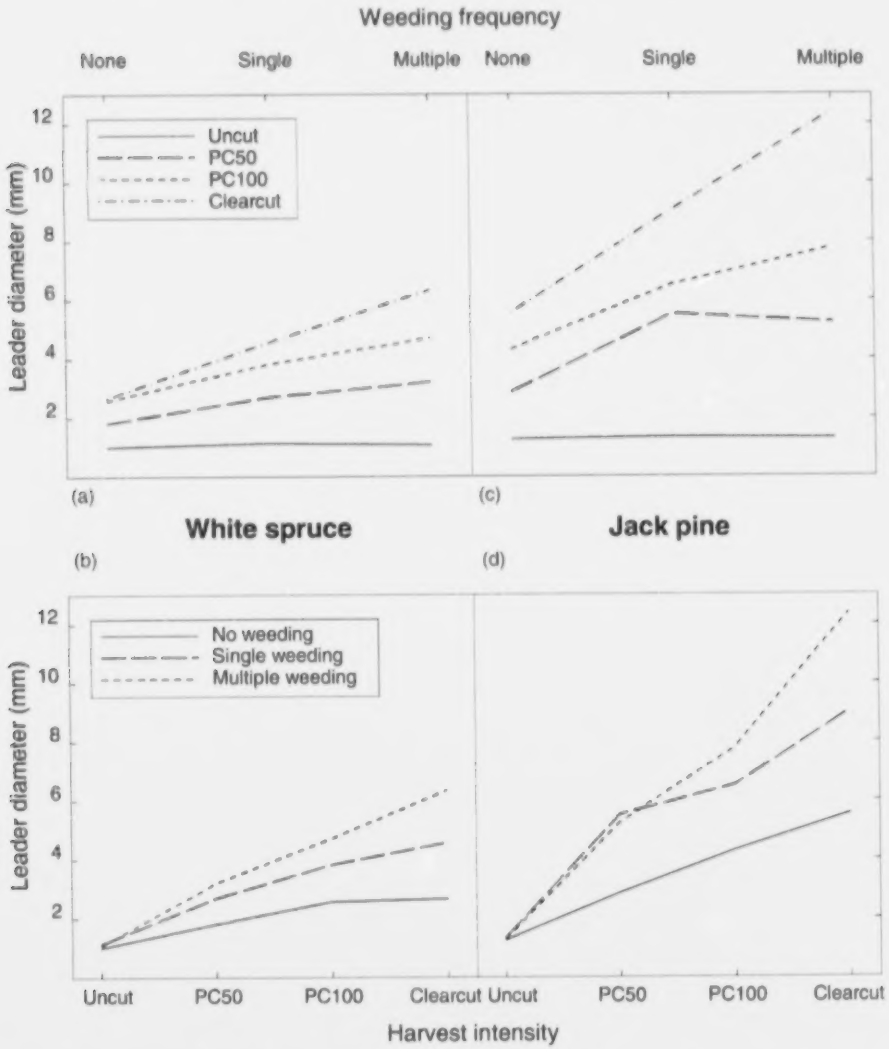

Fig. 3. Mean leader diameter of white spruce and jack pine seedlings in response to weeding frequency and harvest intensity.

PC100 treatment (6.2 mm) was significantly greater than that in the PC50 treatment (4.5 mm). Jack pine mean diameter in weeded plots (6.2 mm) was significantly greater than that in unweeded plots (3.5 mm) (Table 4 and Fig. 3d). Although the contrast between single and multiple weeding may not be directly interpreted, multiple weeding was associated with a diameter advantage only in the PC100 and clearcut treatments (Fig. 3d).

3.6. Height of hardwood regeneration

The interaction between harvest intensity and weeding frequency was significant for fifth-year hardwood height (Table 4), and the interaction was disordinal for the two partially cut treatments (Fig. 4a). Mean height in the PC50 treatment (131 cm) was greater than that in the PC100 treatment (78 cm) for unweeded plots, but similar to the PC100 treatment in single- and

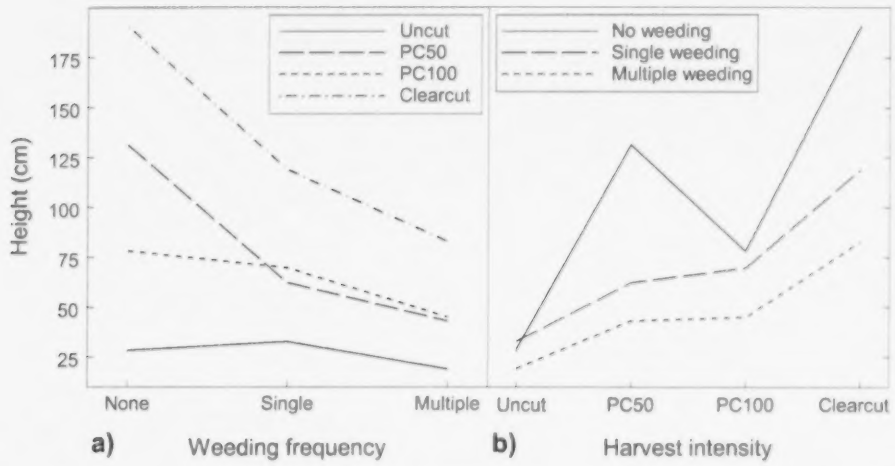

Fig. 4. Mean height of hardwood regeneration in response to weeding frequency and harvest intensity.

multiple-weeded plots. Grouping the partial cuts produces an ordinal interaction (Fig. 4a), allowing interpretation of contrasts for harvest intensity (Table 4). Hardwood mean height in the clearcut treatment (132 cm) was significantly greater than that in the partially cut treatments (71 cm), which in turn was significantly greater than that in the uncut control (27 cm). Mean height in unweeded plots (107 cm) was significantly greater than that in weeded plots (59 cm), and mean height in single-weeded plots (71 cm) was significantly greater than that in multiple-weeded plots (47 cm) (Fig. 4b).

3.7. Density of hardwood regeneration

The interaction between harvest intensity and weeding frequency was significant for fifth-year hardwood density (Table 4). Although the treatment contrasts may not be directly interpreted, hardwood density was greater in the PC100 treatment than in any other

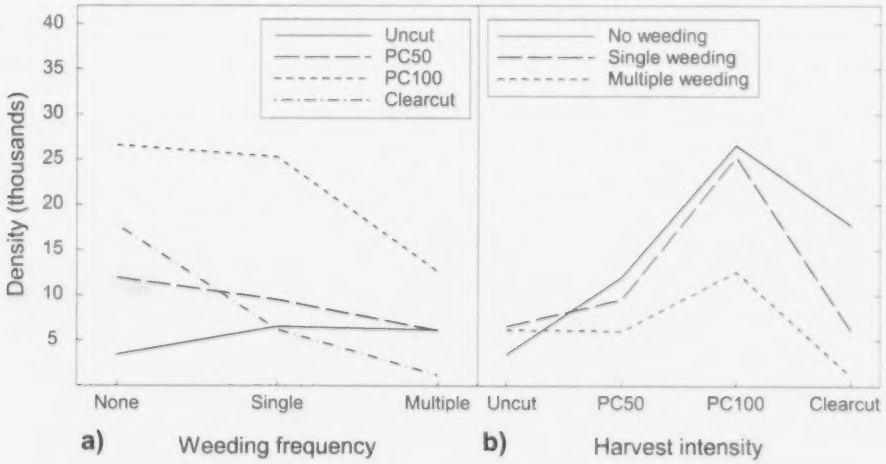

Fig. 5. Mean density of hardwood regeneration in response to weeding frequency and harvest intensity.

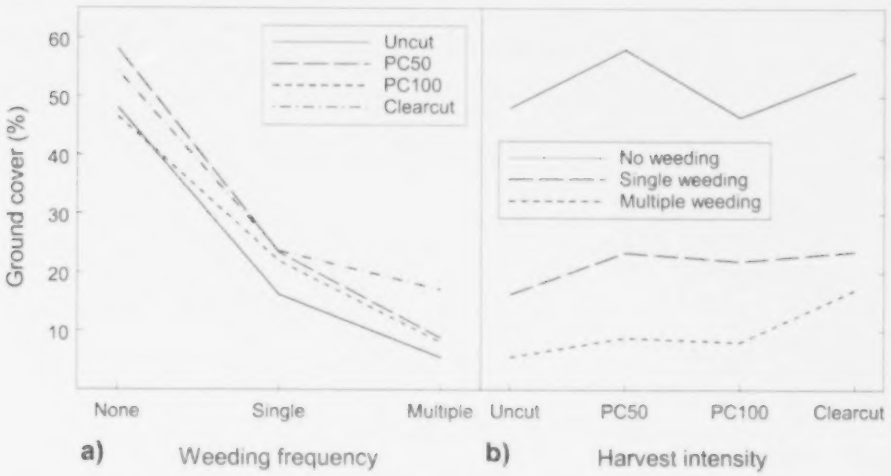

Fig. 6. Mean ground cover of shrubs in response to weeding frequency and harvest intensity.

harvest intensity for all weeding frequencies (Fig. 5a). For example, mean density in the PC100 treatment was 21,449 stems ha^{-1}, compared to only 8325 stems ha^{-1} in the clearcut treatment. Based on the slopes of the lines, the negative effect of weeding on hardwood density became more pronounced as harvest intensity increased (Fig. 5a). Hardwood density generally increased with harvest intensity for all weeding frequencies, but decreased in the clearcut treatment (Fig. 5b).

3.8. Ground cover of shrubs

The effect of harvest intensity on shrub cover was weak, with only the contrast between the clearcut treatment (31.6% cover) and the partially cut treatments (27.8% cover) proving significant (Table 4). It can be inferred from Fig. 6a that shrub cover would also differ significantly between the clearcut treatment and the uncut control. The low responsiveness of shrub cover to harvest intensity is illustrated by the closeness of the lines in Fig. 6a. In contrast, the pronounced decrease in shrub cover with increased weeding frequency is evident from the wide separation of the lines in Fig. 6b. Shrub cover differed significantly between unweeded (51.7% cover) and weeded (15.6% cover) treatments, and between single-weeded (21.3% cover) and multiple-weeded (9.9% cover) treatments (Table 4).

4. Discussion

4.1. Regeneration environment

Windthrow is a major risk associated with partial cutting of mixedwood stands in western Canada (Navratil, 1995). This study confirms the importance of wind damage, which removed up to 17% of the residual basal area following 50% partial cutting (Table 1). Increased understory light associated with this wood loss may favour intolerant hardwood trees and shrubs at the expense of conifers.

Mean values for wind speed (Table 2) are less indicative of windthrow risk than maximum wind speeds occurring in storms. The maximum wind speed measured over the 5 years following treatment was 13.5 km h^{-1}, recorded on the PC100 treatment in the first growing season after the residuals were removed (1997). However, wind speed data were not collected during fall and winter, when more damaging winds may have occurred.

The responsiveness of PAR to canopy opening (Table 2) agreed with results reported by Carlson and Groot (1997) for trembling aspen stands in northern Ontario. PAR was the only microclimatic factor that varied sufficiently among treatments to potentially explain differences in regeneration performance and shrub cover.

Partially cut boreal mixedwood stands may have increased humidity, lower maximum air temperature, and reduced occurrence and severity of frost, compared to clearcut stands (Man and Lieffers, 1999). However, the extent of this moderating effect depends on topographic features and vegetation status. In this study, the small effect of harvesting on mean air temperature, minimum air temperature (frost risk), and mean surface soil temperature was likely attributable in part to sheltering by advance regeneration, saplings, and dead trees, which were left standing on all treatments. Rapid suckering of aspen and development of other vegetation also likely moderated extremes in the regeneration environment. While surface temperatures exceeding 50 °C occur on some clearcuts and are lethal to conifer seedlings (Baker, 1929; Hungerford and Babbitt, 1987; Koppenaal and Colombo, 1989), the maximum temperature in this study was only 25 °C, recorded on the PC100 treatment in the first growing season after the residuals were removed.

4.2. Damage to regeneration

Mixedwood management strategies such as partial cutting and reduced weeding enhance cover and browse for mammals, raising the risk of wildlife damage to regenerating crop trees. For example, growth of shrubs and hardwood trees following disturbance provides shelter for hares, which may seriously damage newly established conifer seedlings (Oxenham, 1983). However, fifth-year data from this study do not indicate increased damage from girdling or browsing associated with any of the treatments (Table 3), despite residual canopies and dense hardwood regeneration. Mammal population densities are often cyclic, and hare damage may be a problem only every 9–10 years (Sullivan et al., 1990). White spruce had less damage than jack pine or hardwoods likely because of its shorter mean height, which resulted in less crown exposed above the snow line for potential browsing by hares. DeLong (2000) reports that white spruce planted under aspen canopies in northern British Columbia may be seriously damaged by hare browsing above the snow line.

Higher incidence of abiotic damage to regeneration on harvested plots than on uncut controls likely resulted from increased windthrow and falling branches after opening the stands. This hypothesis is supported by lower incidence of damage on treatments with less potentially damaging residual overstory (Table 3). Although Froning (1980) reports that 25–56% of spruce advance growth was damaged during mixedwood harvesting, depending on the degree of careful logging measures adopted, in this study the removal of residuals in the PC100 treatment was not associated with increased abiotic damage (Table 3). None of the crop species had more damage in the PC100 treatment than in the PC50 treatment, in which no post-planting harvesting was conducted (Table 3).

There was no pattern of abiotic damage related to scalping, but lower damage was generally associated with increased weeding frequency (Table 3). Weeding may reduce abrasion injury to crop tree regeneration by reducing the density of adjacent vegetation.

4.3. Seedling survival

Survival of white spruce and jack pine regeneration was related to overstory basal area. Consistently low survival rates in the uncut control (Fig. 1) may be explained by low light levels (Table 2) limiting photosynthate availability to support root growth, and hence seedling establishment. Survival for both species was highest in the clearcut and PC50 treatments. Lower survival in the PC100 treatment may have resulted from increased competition for light by the second pulse of aspen suckering (initiated by residual removal), but this possibility is not strongly supported by seedling growth responses (Figs. 2 and 3). Lower survival could also be attributable to disturbance during residual removal, although the level of abiotic damage in the PC100 treatment was similar to that in the other harvest intensities (Table 3).

The fact that jack pine is more shade-intolerant than white spruce (Baker, 1949) may explain its lower survival in the uncut and partially cut treatments. However, factors unrelated to the treatments also contributed to the species differences because jack pine survival was lower even in clearcut stands (Fig. 1).

Lack of significance in the unweeded:weeded contrast for fifth-year survival of white spruce and jack pine (Table 4) agreed with the results of Wagner et al. (1999), who found no effect of weeding on fifth-year survival of tolerant and intolerant conifer seedlings in a northern Ontario clearcut. However, a weeding

effect may develop as hardwood trees and shrubs in the unweeded treatment expand sufficiently around seedlings to cause mortality.

4.4. Seedling growth

Seedling growth differences among treatments likely resulted from differences in understory light availability, which is a key determinant of conifer regeneration success (DeLong, 2000; Claveau et al., 2002; Greene et al., 2002). Jack pine seedlings require full sunlight to attain their maximum potential height growth (Logan, 1966), and white spruce seedlings require 45–100% of full sunlight (Logan, 1969; Johnson, 1986). In this study, growth increased following harvesting and weeding, which enhance light availability. The weeding effect increased with harvest intensity because the abundant understory vegetation promoted by heavy cutting provided a consistently high level of competition to be reduced by weeding.

Weeding significantly affected growth (especially leader diameter) but not survival (Table 1 and Figs. 1–3). Thus, reduced vegetation management may fail to ensure competitive growth rates, despite achieving acceptable conifer stocking in mixedwood stands.

Diameter growth was more responsive than height growth to changes in light level caused by the treatments, confirming the results of other studies (Brand, 1991; Groot, 1999; Wagner et al., 1999). For example, greater seedling growth in the PC100 treatment compared to the PC50 treatment was more apparent for leader diameter than for height (Figs. 2 and 3). The fact that mean diameter in the PC100 treatment exceeded that in the PC50 treatment (Fig. 3) indicates that improved light availability following removal of residuals outweighed the competitive effect of a second pulse of hardwood regeneration.

Since the best seedling growth was associated with clearcutting and multiple weeding, this treatment combination is recommended if the objective is to produce conifer stands. The advantages of vegetation control, particularly multiple weeding, for promoting the growth of conifer plantations across Canada are well documented (DeYoe and Dunsworth, 1988; Brand, 1991; Wagner et al., 1999). However, since boreal mixedwood management objectives include hardwood crop trees, options that reduce herbicide use are preferred.

Groot (1999) also found that growth of white spruce underplanted on mixedwood sites in northern Ontario was poorest under intact overstory, and weeding had little effect on growth in uncut stands. However, while Groot (1999) reports that seedling height growth was more responsive to weeding in partial cuts than in clearcuts, in this study both diameter and height responded better to weeding in clearcuts than in partial cuts. This discrepancy may arise from the use of second-year measurements by Groot (1999), in contrast to fifth-year measurements in this study. For example, DeLong (2000) reports that white spruce height growth in clearcut mixedwood stands in northern British Columbia starts slowly but increases exponentially beyond the third growing season.

4.5. Growth of hardwood regeneration

Hardwood growth differences among treatments largely reflected the suitability of conditions for vegetative reproduction of aspen, which accounted for 91% of hardwood regeneration. Growth patterns were less consistent for hardwood regeneration than for conifer seedlings, but hardwood height and density generally increased with harvest intensity and decreased with weeding frequency (Figs. 4 and 5).

The fact that hardwoods were shorter in the PC100 treatment than the PC50 treatment for unweeded plots (Fig. 4) may be explained by the second pulse of suckering after removal of the residual overstory. This secondary regeneration greatly increased mean density of hardwoods (Fig. 5b), but decreased mean height (Fig. 4b). This decrease was apparent only in the unweeded treatment because it had the tallest hardwood regeneration and thus reflected the effect of an influx of shorter stems. Lower hardwood density in the clearcut treatment compared to the uncut control for weeded plots (Fig. 5b) may be attributable to more uniform distribution of herbicide in the absence of interference from canopy tree stems.

Initiation and development of aspen suckers depend on adequate surface soil temperature and light intensity (Burns and Honkala, 1990). However, dense suckering followed the PC100 removal cut, despite surface shading by the original suckers and other vegetation established since the initial cut. Thus, final removal cuts on mixedwood sites should be delayed

until underplanted conifer seedlings are tall enough to withstand increased hardwood competition.

The fact that mean height of hardwood regeneration was lower for partial cutting with single weeding (66 cm) than for clearcutting with multiple weeding (93 cm) (Fig. 4) suggests that partial cutting may be an alternative to herbicides for controlling excessive hardwood growth in boreal mixedwood stands. However, the effectiveness of this option is not supported by the data for hardwood density and conifer growth. Mean hardwood density for partial cutting with single weeding was 17,330 stems ha^{-1}, compared to 1094 stems ha^{-1} for clearcutting with multiple weeding, and seedling height for partial cutting with single weeding averaged about half of that for clearcutting with multiple weeding.

4.6. Ground cover of shrubs

Shrub cover averaged 50–60% for all harvest intensities in unweeded plots (Fig. 6). While cover remained consistent, composition shifted from shade-tolerant species, such as mountain maple and beaked hazel, to shade-intolerant species, such as red raspberry (*Rubus idaeus* L.) and pin cherry (*Prunus pensylvanica* [L.] fil), as harvest intensity increased. The sharp decrease in shrub cover with weeding frequency for all harvest intensities (Fig. 6a) contrasted with the lack of response to harvesting for all weeding frequencies (Fig. 6b). This indicates that traditional weeding techniques are more effective than partial cutting for controlling perennial competitors on boreal mixedwood sites. While most of the effect was accomplished by a single weeding, the continued decline in shrub cover with multiple weeding highlights the need to adapt weeding frequency to the regrowth potential of the shrub species on a particular site.

4.7. Implications for mixedwood management

Alternative regeneration practices involving partial cutting, underplanting, and reduced weeding may be considered for maintaining conifers in Ontario's boreal mixedwood stands. In this study, these practices did not promote regeneration damage, but they increased residual volume loss to windthrow. Removing residual overstory prematurely may cause inadequately established conifer seedlings to be overcome by a second pulse of hardwood suckering. White spruce regeneration must be at least 2.5 m tall to compete with new aspen suckers and shrubs after release (Johnson, 1986). However, delaying the removal cut too long could increase susceptibility of crop trees to harvesting damage. Underplanting uncut boreal mixedwood stands with white spruce or jack pine is not recommended because high seedling mortality is associated with the correspondingly low light levels.

While partial cutting with reduced weeding was acceptable in terms of crop tree survival, growth of planted spruce and pine seedlings was favoured by maximizing harvest intensity and weeding frequency. Furthermore, weeding after partial cutting requires costly ground application of herbicides to avoid damaging residual hardwood trees. However, partial cutting may favour establishment of natural conifer regeneration (Ball and Walker, 1995; Harvey et al., 2002).

To maintain height parity between planted white spruce seedlings and natural hardwood regeneration, multiple weeding may be required in both clearcut and partially cut boreal mixedwood stands. However, a single weeding appears adequate for jack pine. The stress-tolerant strategy (Grime, 1977) of white spruce enables it to survive under hardwood regeneration for many years until self-thinning of the hardwoods increases the light available to support accelerated growth. White spruce's photosynthetic system has adapted to use periods of high light in the understory prior to leaf-out and after leaf-fall of the hardwood canopy (Man and Lieffers, 1997). In contrast, the ruderal strategy (Grime, 1977) of jack pine is characterized by rapid resource acquisition and dominance of the local environment. For example, Wagner et al. (1999) found that intolerant conifers such as jack pine are more competitive than tolerant conifers and require fewer years of vegetation control to achieve maximum size.

If white spruce's role as an understory species is acceptable, then a single weeding may be adequate to maintain conifers in regenerating boreal mixedwood stands. Jack pine required this weeding to restrict the height of neighbouring hardwoods, enabling it to express its ruderal strategy. A single weeding was also required to reduce shrub cover below 50%, and relatively less shrub reduction was accomplished by

subsequent weedings (Fig. 6). Seedlings released with glyphosate are likely to maintain their growth advantage because succession to uncompetitive non-woody vegetation is promoted (Reynolds et al., 2000).

White spruce planted in partially cut mature mixedwood stands in central Alberta had greater height and diameter increments than those planted in clearcut or uncut stands (Man and Lieffers, 1999). However, residual trees can reduce the growth of planted white spruce and their competitors (Kabzems and Lousier, 1992). In this study, partial cutting (with or without removal of residuals) provided no growth advantage to underplanted conifer seedlings. If no weeding was conducted, mean sucker density fell from 18,000 stems ha^{-1} in the clearcut to 12,000 stems ha^{-1} in the PC50 treatment (Fig. 5). However, mean height of suckers in the PC50 treatment was 131 cm, considerably exceeding that of white spruce (41 cm) and jack pine (67 cm).

The single weeding required as a minimum for conifer establishment also produced acceptable density and height of hardwood crop tree regeneration. Multiple weeding cannot be recommended for mixedwood management because it reduced fifth-year hardwood height below 1 m and fifth-year hardwood density below 10,000 stems ha^{-1}. Although this low stocking would minimize whipping damage to conifer seedling leaders (Coopersmith and Hall, 1999), it may be inadequate to produce sufficient well-spaced hardwood crop trees at maturity (Peterson and Peterson, 1995).

In western Canada, underplanting aspen stands with white spruce may lower site preparation and vegetation management costs, improve seedling nutrient status, and reduce seedling damage from root rot and frost (Tanner et al., 1996). White spruce could be established 20 years prior to harvesting the hardwood overstory (DeLong, 2000), avoiding competition from hardwood regeneration during spruce establishment. However, this study indicates that underplanting uncut boreal mixedwood stands in Ontario could result in unacceptably high conifer seedling mortality. Underplanted white spruce mortality averaged 54% for uncut stands, compared to only 6% in British Columbia (DeLong, 2000). This discrepancy is likely explained by low understory light levels in eastern Canada (Greene et al., 2002). Values ranging from 2 to 23% of above-canopy light are reported for mature aspen stands in eastern Canada (Messier et al., 1998; Groot, 1999). The instrumented uncut stand in this study had only 6% of the understory light recorded in the clearcut (Table 2). Besides the disadvantage of prolonged low light levels, early underplanting requires costly road maintenance for separate regeneration and harvesting operations. These considerations highlight the challenges involved in establishing blended mixtures of conifers and hardwoods.

If mixedwood objectives include maximizing current annual increment of the component species, then a mosaic of alternating conifer and hardwood patches or corridors should be considered. Treatments could be adapted to the silvics of the individual species more effectively in mosaics than in blended mixtures. Furthermore, in blended mixtures aspen competition may delay the spruce rotation age by 30–40 years compared to pure stands (Johnson, 1986). Frivold and Frank (2002) were unable to detect any volume growth advantages to conifers when grown in blended mixtures with hardwoods. In the mosaic scenario, hardwood portions would be clearcut to maximize natural regeneration and would not be weeded, preventing herbicide damage to young crop trees. Conifer portions could be clearcut or partially cut, depending on ecological and economic considerations. For example, partial cutting boreal mixedwood stands has negative pathological implications (McLaughlin and Dumas, 1996), but may enhance natural conifer regeneration or wildlife habitat. The choice between single and multiple weeding in conifer portions would depend on competition intensity, accessibility, and public concern about herbicide use. Eliminating hardwood cover from conifer portions of the mosaic would reduce shelter from predators, limiting populations of small mammals that damage seedlings.

According to Smith et al. (1997), species with similar shade tolerances and growth rates should be established in separate patches to avoid the gradual dominance by one species causing the other to become a costly filler. Spatial separation would be an effective approach for pine and aspen because their common ruderal strategy increases the potential for mutual interference. The shade-tolerance of spruce permits closer integration with intolerant hardwoods (i.e., small patches or narrow corridors). Alternating corridors of spruce and aspen would support application of a dual rotation system in which aspen is harvested

every entry (e.g., 50-year intervals) and spruce is harvested every second entry.

Site preparation improves the establishment of natural conifer regeneration in mixedwood stands (Stewart et al., 2000; Nilsson et al., 2002), but may be less effective for artificial regeneration. Although site preparation decreases mortality and improves growth of white spruce planted in Alberta mixedwood stands (Man and Lieffers, 1999), in this study scalping was not significant as a main effect or as a component of an interaction. DeLong (2000) also reports no effect of scalping on growth of white spruce planted under aspen. Furthermore, exposing mineral soil during site preparation prior to planting spruce increases the potential for frost heaving and improves site conditions for competitor establishment (Kabzems and Lousier, 1992). Since scalping on boreal mixedwood sites reduces soil organic matter and respiration rate (Mallik and Hu, 1997), soil biological activity may be adversely affected. Although pre-planting scalping improves contact between fine roots and mineral soil, it may accelerate water loss from some soil types (Flint and Childs, 1987). Thus, scalping prior to planting in uncut or carefully logged boreal mixedwood stands does not seem to provide any biological advantages to white spruce or jack pine seedlings.

5. Conclusion

The hypothesis that a combination of partial cutting, scalping, underplanting, and low-frequency chemical weeding achieves optimum stocking and growth of mixed conifer and hardwood regeneration was not fully supported by the results of this study. Optimum growth of spruce and pine seedlings was achieved by clearcutting and frequent weeding, while scalping provided no benefit. Frequent weeding is not an acceptable option for producing integrated species mixtures because of associated declines in stocking, growth, and quality of hardwood crop trees. Thus, separation of species into patches or corridors may be more effective than blended mixtures because it permits silvicultural treatments to be suited to the needs of each species, while retaining diversity within stands. Controlled studies are required to compare the effectiveness of blended mixtures and patchwork mosaics for establishing mixed stands of conifers and hardwoods.

The complex dynamics typical of mixed-species stands necessitates long-term monitoring of regeneration to properly evaluate management alternatives. For example, based on the 5-year results reported here, jack pine had unexpectedly high survival (70–80%) and superior growth to white spruce in partially cut mixedwood stands. However, several years of monitoring are required to determine the ultimate success of each conifer and hardwood crop species as stand development progresses.

Research is also required to determine whether the results reported here are transferable to other boreal mixedwood sites with coarser or finer soils, higher proportions of conifers or white birch in the overstory, or more balsam fir competition in the understory. Logging damage to regeneration in multiple-entry partial cutting systems also needs to be investigated.

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